Restoration Research

Research advances the sciences that guide restoration. This, in turn, often results in the development of new methods for implementing and monitoring restoration projects. These new methods are incorporated into restoration programs through pilot studies or experimental designs that can further improve our understanding. A coordinated experimental research program can explain patterns in monitoring data. In addition, by incorporating the principles of adaptive management into the experimental approach, scientists can suggest corrective measures that can lead to improved restoration results in other efforts in similar ecosystems. Because restoration science is still relatively young, experimentation at restoration sites by restoration programs offers an important opportunity to learn by doing.

The ingredients for a successful research program are a funding sponsor, a stable knowledge base (i.e., institutional knowledge), ongoing monitoring programs, and extensive resources for field studies (i.e., labor and equipment). Most often, these circumstances coalesce in a university setting, with leadership provided by a prominent faculty member and support provided by graduate students, postdoctoral associates, and collaborators. Often, these programs integrate National Estuarine Research Reserve (NERR) support and study sites. Prominent examples include Rutgers University programs involved in Delaware Bay marsh restoration through the Public Service Enterprise Group and San Diego State University's Pacific Estuarine Research Laboratory on southern California wetlands. Other research institutions involved in coastal restoration research include the following:

- National Oceanic and Atmospheric Administration (NOAA) Center for Coastal Fisheries and Habitat Research, Beaufort, North Carolina
- U.S. Geological Survey (USGS) National Wetlands Research Center, Lafayette, Louisiana
- National Coral Reef Institute, Fort Lauderdale, Florida
- Oregon Institute of Marine Biology, Charleston
- Jackson Estuarine Lab, University of New Hampshire, Durham
- Virginia Institute of Marine Science, Gloucester Point
- Wetland Ecosystem Team, University of Washington, Seattle
- Coastal Research Lab, University of New Orleans, Louisiana.

Federally funded programs that are nationally and regionally significant have been instituted to promote the study and protection of estuarine areas and to develop restoration tools and technologies. These programs, discussed below, offer opportunities for research, collaboration, and restoration project funding.

The NERR program was established by the Coastal Zone Management Act of 1972 to protect and study estuarine areas through a network of 25 reserves from different biogeographic regions of the United States (http://coastalmanagement.noaa.gov/). One focus topic for the program is habitat restoration (http://www.ocrm.nos.noaa.gov/nerr/issues.html). An inventory of restoration activities within the NERR program is currently underway. At several reserves, restoration research is currently being conducted. These reserves include the Tijuana River, California (http://www.tijuanaestuary.com/); South Slough, Oregon (www.southsloughestuary.org); and Rookery Bay, Florida (www.rookerybay.org)

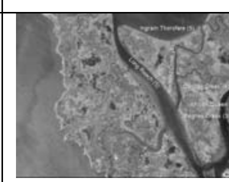
The Cooperative Institute for Coastal and Estuarine Environmental Technology supports the scientific development of innovative technologies for understanding and reversing the impacts of coastal and estuarine contamination and degradation. In addition, the institute develops approaches for restoring habitats (http://ciceet.unh.edu).

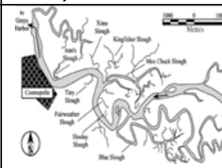
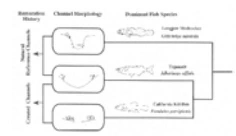
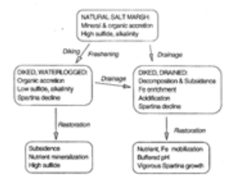
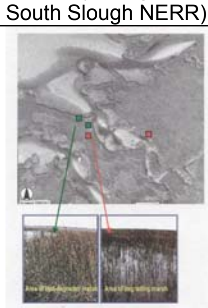
The Coastal Restoration and Enhancement through Science and Technology program in Louisiana and Mississippi is a research initiative developed through an alliance between NOAA, 11 universities, and the USGS National Wetlands Research Center. The program office opened in 2002, and the first call for proposals is expected in 2003. The program's goal is to integrate research to improve coastal habitat restoration through the following:

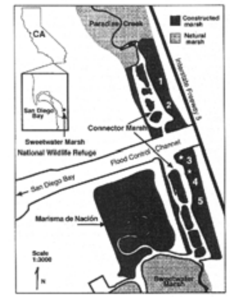
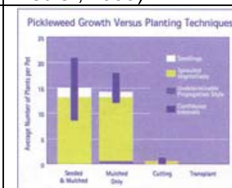
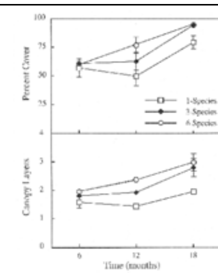
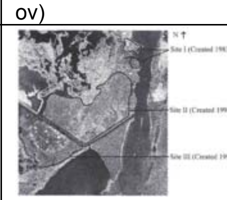
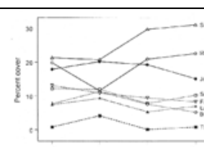
- better coordination of programs and projects
- assessment and improvement of existing methods
- development of new approaches and modeling
- improvement of tools, communications, and outreach
- increased understanding between scientists, managers, and the public.

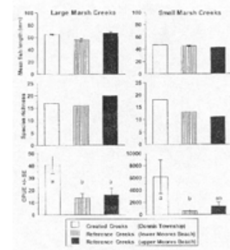
The NOAA Restoration Research Program, part of the NOAA Restoration Center, was developed to advance the science of restoration ecology in coastal habitats (http://www.nmfs.noaa.gov/habitat/restoration/projects_programs/research/index.html). The program supports research on coastal ecosystem structure and function. Specifically, the program focuses on studying the recovery process of restored coastal habitats, developing and testing innovative restoration methods, and establishing success criteria and monitoring protocols. Staff from the NOAA Fisheries Science Centers and the NOAA Office of Habitat Conservation work in partnership with the scientific community to provide expertise in developing improved restoration techniques.

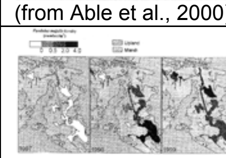
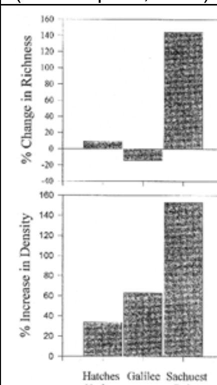
Table 1 provides a list of various studies, organized by habitat type, conducted to improve the understanding and methodology of restoration.

Research Focus	**Description**	**Location**	**Author, Citation and/or URL**	**Photo**
Salt Marsh – Hydrology restoration and tidal channel development				
Tidal marsh channel development	Set up experimental design to evaluate marsh colonization rates and fish use in created channels versus channels allowed to develop naturally (ongoing).	Tijuana Estuary, California	Vivian-Smith, 2001, In: *Handbook for Restoring Tidal Wetlands*, Zedler (ed), CRC Press; pp. 39-88.	 (courtesy Jeff Crooks, Tijuana River NERR)
Channel morphometry (i.e., measurement of channel shape)	Examined a natural tidal marsh channel network (1039 channel segments) to identify principles that can be applied to restoration projects.	Cape May Peninsula, New Jersey	Zeff, 1999, *Restoration Ecology* 7(2):205-211.	 (modified from Zeff, 1999)
Evolution of restored dike-breached marshes	Reviewed 15 re-flooded sites to allow prediction of marsh evolution rates and establishment patterns of tidal channel systems.	San Francisco Bay, California	Williams and Orr, 2002, *Restoration Ecology* 10(3):527-542.	 (from Williams and Orr, 2002)

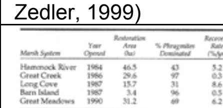
Developing hydraulic geometry relationships between tidal flows and channel geometry	Collected data from existing and historic (using old maps) mature marshes to predict the direction and rate of evolution in immature or disturbed systems.	San Francisco Bay, California	Williams et al., 2002, *Restoration Ecology*, 10(3):577-590.	 (from Williams et al., 2002)
Linking slough geometry and ecological processes	Measured ebb flow, exit time of floating detritus, organic content of bed sediments, and benthic community structure in sloughs of various size and structure to inform restoration design.	Chehalis River, Washington	Hood, 2002, *Canadian Journal of Fisheries and Aquatic Sciences* 59:1418-1427.	 (from Hood, 2002)
Influence of channel morphology on fish use	Explored relationships between channel habitat characteristics, such as channel order, width, depth, bank slope, water quality, and sediment composition and fish use to provide recommendations for future restoration.	San Diego Bay, California	Williams and Zedler 1999 *Estuaries* 22(3A):702-716 and Williams and Desmond, 2001 In: *Handbook for Restoring Tidal Wetlands*, Zedler (ed), CRC Press; pp.235-269.	 (from Williams and Desmond, 2001)
Temporary detrimental effects of restoring tidal hydrology on water quality	Exposed drained peat cores from diked-waterlogged marshes to salt water in a greenhouse experiment resulting in decreased vigor of transplanted *Spartina alternaflora.*	Cape Cod, Massachusetts	Portney, 1999, *Environmental Management* 24(1):111-120.	 (from Portney, 1999)
Salt Marsh – Elevation manipulation				
Effect of elevation on salt marsh recovery after diking and subsidence	Graded marshes to three elevations using dike material. Found mid-elevation marshes to have both rapid vegetation colonization and tidal channel development.	South Slough, Oregon	Cornu and Sadro, 2002, *Restoration Ecology* 10(3):474-486.	 (courtesy Craig Cornu, South Slough NERR)
Effect of thin layer sediment deposition on deteriorating salt marsh	Determined that the placement of dredged material in tidal marshes could offset marsh deterioration associated with sediment deficits and sea level rise without negatively impacting adjacent "healthy" marsh.	Masonboro Island, North Carolina	http://ciceet.unh.edu/files/full_project/LeonardFinal.pdf and http://people.uncw.edu/lynnl/ciceet.htm	 (from CICEET website)
Salt Marsh – Plant ecology				

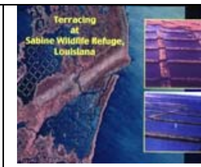
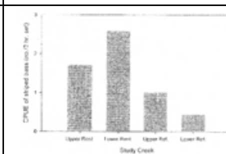
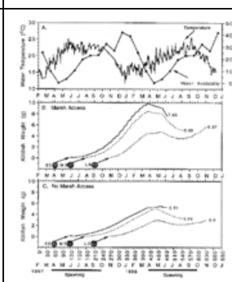
Use of soil amendments for increasing establishment, growth, and function of salt-marsh vegetation	Found that added nitrogen increased the short-term growth of *Spartina foliosa* and *Salicornia bigelovii*, but little effect on long-term growth or accumulation of soil organic matter or nutrients.	San Diego Bay, California	Boyer and Zedler, 1999, *Restoration Ecology* 7(1):74-85. Boyer et al., 2000, *Estuaries* 23:711-721.	 (from Boyer and Zedler, 1999)
Improve pickleweed establishment	Compared soil enrichment and propagation techniques for pickleweed (*Salicornia virginica)*. Found that pickleweed mulch rototilled into the soil increased establishment over transplanting or cuttings.	Suisin Bay, California	Disney and Miles, 2000, *State of the Estuary (San Francisco Bay) Restoration Primer,* p. 50.	 (from Disney and Miles, 2000)
Importance of diversity in salt marsh restoration	Compared the effects of species richness on ecosystem function. Found that a high-diversity of seedlings resulted in more complex canopies, increased biomass, and increased nitrogen accumulation.	Tijuana Estuary, California	Sullivan, 2001, In: *Handbook for Restoring Tidal Wetlands*. Zedler (ed), CRC Press; pp. 119-155.	 (from Sullivan, 2001)
Develop successful marsh planting configurations	Evaluated influence of different planting configurations of *Spartina alterniflora* on coverage rates and access to the marsh surface by fish (ongoing).	Eastern Neck National Wildlife Refuge, Chesapeake Bay, Maryland	http://www.nmfs.noaa.gov/habitat/restoration/projects_programs/research/funded_projects/5.html	 (from http://www.nmfs.noaa.gov)
Compare genetic diversity of *Spartina alterniflora* on restored and natural sites	Evaluated the genetic diversity of native plants that have colonized salt marshes constructed from dredge sediments. Found that genetic diversity of was comparable with natural populations.	Sabine National Wildlife Refuge, Louisiana	Travis et al., 2002, *Restoration Ecology* 10(1):37-42.	 (from Travis et al., 2002)
Natural seedling recruitment in restored sites	Found that favorable physical conditions alone were not enough to establish species-rich salt marsh vegetation. With the possible exception of perennial pickleweed (*Salicornia virginica),* most salt marsh plants should be sown or planted to ensure establishment.	Tijuana Estuary, California	Lindig-Cisneros and Zedler, 2002, *Estuaries* 25(6A):1174-1183.	 (from Lindig-Cisneros and Zedler, 2002)

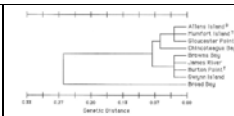
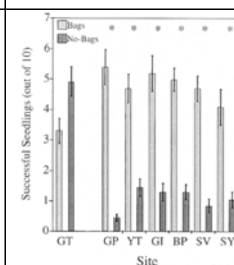
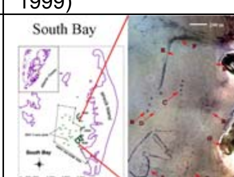
<table>
<tr><td>Develop a seed-based system of propagating Spartina alterniflora over large areas with improved performance</td><td>Tested artificial seed production and evaluated clones with high seedling vigor and exceptional resistance to disease.</td><td>Louisiana</td><td>Harrison et al., 2001, Louisiana Agriculture 44(3):4-6.</td><td>
(courtesy Michael Materne, USDA NRCS 2001)</td></tr>
<tr><td colspan="5">Salt Marsh – Fish and invertebrate growth and habitat use</td></tr>
<tr><td>Changes in fish populations after restoring tidal flow</td><td>Compared species composition, richness, abundance, and size in a restored marsh and a reference marsh. Found that all parameters were either the same or greater in the restored marsh.</td><td>Delaware Bay, New Jersey</td><td>Able et al., 2000 In: Concepts and Controversies in Tidal Marsh Ecology, Weinstein and Kreeger (eds), Klewer Academic Publishers, pp. 749-773.</td><td>

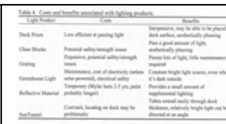
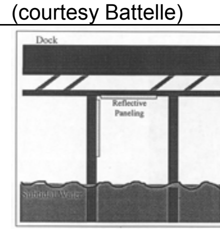
(from Able et al., 2000)</td></tr>
<tr><td>Changes in fish and crustaceans populations after restoring tidal flow</td><td>Found that restoration resulted in rapid changes in the composition, density, size, and distribution of fish and crustaceans.</td><td>Narragansett, Rhode Island</td><td>Raposa, 2002, Restoration Ecology 10(4):665-676.</td><td>
(from Raposa, 2002)</td></tr>
<tr><td>Effect of different tidal restrictions on fish community composition</td><td>Compared fish and decapod crustacean utilization along a gradient of tide-restricted and subsequently restored marshes. Found that species richness increased with restoration only at the most tide-restricted site.</td><td>Provincetown, Massachusetts and southern Rhode Island</td><td>Raposa and Roman, 2003, Estuaries 26(1):98-105.</td><td>

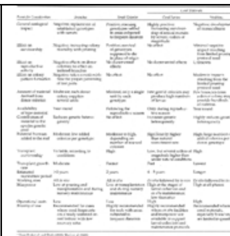
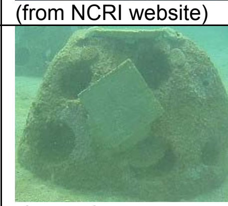
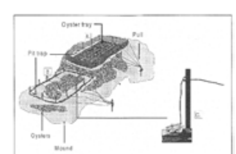
(from Raposa and Roman 2003)</td></tr>
<tr><td>Fish assemblages in restored marsh</td><td>Found that fish assemblages peaked soon after restoration, then later declined as sediment and hydrologic processes changed and stabilized.</td><td></td><td>Williams and Zedler, 1999, Estuaries 22(3A):702-716.</td><td>

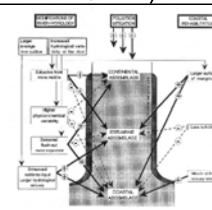
(from Williams and Zedler, 1999)</td></tr>
<tr><td>Long-term monitoring of salt marsh restoration</td><td>Found fish assemblages may take over a decade to reach those found in natural marshes.</td><td>Long Island and Fisher's Island Sounds, Connecticut</td><td>Warren et al., 2002, Restoration Ecology 10(3):497-513.</td><td>
<table><tr><th>Marsh System</th><th>Year Opened</th><th>Restoration Area (ha)</th><th>% Phragmites Dominated</th><th>Recovery Rate (%/yr)</th></tr><tr><td>Hammock River</td><td>1984</td><td>46.5</td><td>43</td><td>5.2</td></tr><tr><td>Great Creek</td><td>1986</td><td>29.6</td><td>97</td><td>0.3</td></tr><tr><td>Long Cove</td><td>1987</td><td>15.7</td><td>31</td><td>8.6</td></tr><tr><td>Barn Island</td><td>1987</td><td>3.4</td><td>96</td><td>0.5</td></tr><tr><td>Great Meadows</td><td>1990</td><td>31.2</td><td>69</td><td>6.2</td></tr></table>All sites were 100% Phragmites before tidal restoration.
(from Warren et al., 2002)</td></tr>
</table>

Marsh terracing for creating fish habitat	Found greater abundances of some fish species associated with the marshes of the terrace field than with the unvegetated shallow water habitat. Experimenting in 2003 with smaller terrace cell size to increase the amount of marsh area in the terrace field.	Sabine National Wildlife Refuge, Louisiana and Galveston Island State Park	Rozas and Minello, 2001, *Wetlands* 21(3):327-341 and http://galveston.ssp.nmfs.gov/ecology/Projects/Current/C3_effectofcellsizeterrance.htm..	 (from http://galveston.ssp.nmfs.gov/)
	Measured fishery distribution patterns in order to estimate potential populations in restored marshes with various channel configurations.		Minello and Rozas, 2002, *Ecological Applications* 12(2):441-455.	
Movements and food habits of striped bass (*Morone saxatilis*)	Found that creek use and diets of striped bass were similar in natural and restored marshes.	Delaware Bay, New Jersey	Tupper and Able, 2000, *Marine Biology* 137:1049-1058.	 (from Tupper and Able, 2000)
Functional performance of restored marshes over time	Compared fish densities, prey resources, and diet composition at three restored marshes of varying ages and a natural marsh. Found a pulse of productivity 2-3 years after restoration, but differences were still present between the restored and natural marshes after 20 years.	Salmon River, Oregon	Gray et al., 2002, *Restoration Ecology* 10(3):514-526.	
Food web analysis and improving trophic function	Used stable isotope analysis to assess food web in restored marshes; added organic matter such as alfalfa, peat, kelp, or sewage to soils to “jumpstart” the marsh’s food chain by increasing microalgal growth; and “seeded” invertebrates that are slow to develop.	Mission Bay and Tijuana Estuary, California	Levin and Currin, http://ciceet.unh.edu/progressreports/2003/3_2003/levin2000/index.html and http://www.nmfs.noaa.gov/habitat/restoration/projects_programs/research/funded_projects/4.html	
Determine the value of marsh area and accessibility for fish	Developed, tested, and applied a bioenergetics model for the California killfish (*Fundulus parvipinnis)*, with potential use in designing salt-marsh restoration.	Tijuana Estuary, California	Madon et al., 2001, *Ecological Modelling* 136(2-3):149-165.	 (from Madon et al., 2001)
Contribution of	Used mass-balance model to	University of	Gray, personal	

marsh habitats to fish growth	determine how marshes in different stages of recovery contribute to the growth of juvenile salmon.	Washington	communication, 2003 (ayesha@u.washington.edu).	
Seagrass – Genetics				
Genetic diversity and structure of natural and transplanted eelgrass beds	Found little reduction in genetic diversity in Chesapeake Bay transplantations; potentially due to use of seeds and seedling recruitment.	Chesapeake and Chincoteague Bays	Williams and Orth, 1998, *Estuaries* 21(1):118-128.	 (from Williams and Orth, 1998)
Genetic diversity of transplanted eelgrass (*Zostera marina*) populations	Found that transplanted eelgrass populations with higher genetic diversity developed more flowering shoots, achieved greater seed germination, and had a higher leaf-shoot density.	Southern California, Chesapeake Bay, and New Hampshire	Williams, 2001, *Ecological Applications* 11(5):1472-1488.	
Seagrass – Seeds for restoration				
Mechanized seed planter	Developed method for mixing seeds with a media then pumping them just below the sediment surface. Currently testing organic versus inorganic medium.	University of Rhode Island	Nixon et al., 2002, http://ciceet.unh.edu/progressreports/2002/fall/nixon98/index.html	 (photo: CICEET)
Protecting seeds from predation, burial, and transport	Planted seeds with burlap (1.0-mm mesh size) covering them. Found that seeds survived 26% to 51% better than seeds without protection.	York and Piankatank Rivers, Chesapeake Bay	Harwell and Orth, 1999, *Aquatic Botany* 64(1):51-61.	 (from Harwell and Orth, 1999)
Broadcasting seeds from a boat	Planted 9.1 million seeds in 74 1-acre plots. The plots were visible from preliminary aerial photo monitoring.	Chesapeake Bay	Orth, 2003, presented at 1st National Estuarine Restoration Conference, Baltimore, Maryland. More information available online at http://www.vims.edu/bio/sav/	 (courtesy Bob Orth, Virginia Institute of Marine Science)
Seagrass – Transplant methods				
Improve success and cost effectiveness of transplanting adult eelgrass	Developed and tested the Transplanting Eelgrass Remotely with Frame System (TERFS), where 200 eelgrass shoots are tied to a wire frame and dropped into place from a boat. Preliminary	New Hampshire	Short, 2003, presented at 1st National Estuarine Restoration Conference, Baltimore, Maryland	 (courtesy Fred Short, University of New

	results show that eelgrass is increasing at the 1-acre sites.			Hampshire)
Restore eelgrass in areas of propeller scars and vessel groundings	Placed bird roosting stakes in transplanted areas to provide a source of natural fertilization and compared to application of water-soluble fertilizers. Found the bird stakes produced the highest recovery rates for *Halodule wrightii*.	South Florida	Kenworthy et al., 2000, technical report available online at http://shrimp.bea.nmfs.gov/~mfonseca/lvfinalreport.pdf	 (courtesy Kevin Kirsch, NOAA).
	Tested the effectiveness of placing sediment-filled, biodegradable fabric tubes to deploy fine sediment and prevent further erosion.	Florida Keys National Marine Sanctuary	Hammerstrom, personal communication, 2003 Kamille.Hammerstrom@noaa.gov	 (courtesy Kamille Hammerstrom, NOAA)
Seagrass – Improving conditions for restoration				
Increasing light under piers	Compared solar tubes, deck prisms, and electric light. Found that solar tubes were the most cost effective alternative.	Sequim, Washington	Blanton et al., 2002, technical report available online at http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13714.pdf	 (from Blanton et al., 2002)
	Placed glass blocks in new portion of pier and planted eelgrass under area of blocks. Eelgrass survived the first year; monitoring is ongoing.	Clinton, Washington	Thom et al., 2003, presented at Puget Sound Research Conference. Available 2004 online at http://www.psat.wa.gov	 (courtesy Battelle)
	Evaluated the use of reflective materials under the structure. Found that light was increased and eelgrass growth was observed.	Anacortes, Washington	Gayaldo et al., 2001, presented at Puget Sound Research Conference. Available online at http://www.psat.wa.gov/Publications/01_proceedings/sessions/poster/i_gayald.pdf	 (from Gayaldo et al., 2001)
Reef research				

Mariculture of clonal coral fragments	Developed methods for growing and transplanting coral fragments and gravid colonies in the laboratory and in the field.	Northern Red Sea	Rinkevich, 1995, *Restoration Ecology* 3(4):241-251. Epstein et al., 2001, *Restoration Ecology* 9(4):432-442.	 (from Epstein et al., 2001)
Reattachment of corals after vessel grounding	Monitored reattached, tagged coral to determine size and health. Compared results to undamaged sites.	Fort Lauderdale, Florida	Gilliam et al., date unknown, http://www.nova.edu/ocean/ncri/index.html	 (from NCRI website)
	Monitored growth and survival of stony coral transplants and donor colonies.	Fort Lauderdale, Florida	Glynn et al., date unknown, http://www.nova.edu/ocean/ncri/index.html	 (from NCRI website)
	Examined the effects of reef structure on fish assemblages, the effects of coral larval attractants on coral recruitment, and the interaction between fish assemblages and coral recruitment.	Fort Lauderdale, Florida	Quinn et al., date unknown, http://www.nova.edu/ocean/ncri/index.html	 (from NCRI website)
Global review of coral transplant projects	Recommended transplanting only when natural recovery fails and specified types of coral that transplant better than others (e.g., massive species better than branching species).	Global	Edwards and Clark, 1998, *Marine Pollution Bulletin* 37(8-12):474-487.	 (from Edwards and Clark, 1998)
Oyster Reef research				
Characteristics of intertidal oyster reef formation and subsequent use by resident and transient species	Found that a living habitat was formed by oyster settlement on constructed experimental reef within three years. A conceptual model will be developed to describe reef succession and function.	South Carolina	Coen et al., 1999 in Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches, Luckenback et al. (eds), Virginia Institute of Marine Science Press, pp. 133-158 and	 (from Coen et al., 1999)

			http://www.dnr.state.sc.us/marine/mrri/shellfish/reefold.htm.	
Mangrove research				
Natural recovery with hydrology restoration	Found that if hydrology was restored planting was only necessary if seeds or seedlings were not able to reach the restoration site.	Fort Lauderdale, Florida	Lewis and Streever, 2000, technical report available online at http://www.wes.army.mil/el/wrtc/wrp/tnotes/vnrs3-2.pdf	 (from Lewis and Streever, 2000)
Effect of coastal restoration measures on fish assemblages	Found that mangrove restoration increased organic inputs and positively affected estuarine and coastal fish assemblages, but had no effect on fish in the upper estuary and wetlands.	Southeast Asia	Baran and Hambrey, 1998, *Marine Pollution Bulletin* 37(8-12):431-440.	 (from Baran and Hambrey 1998)

Additional information is available in:

Borde, A.B. L.K. O'Rourke, G.W. Williams, R.M. Thom, and H.L. Diefenderfer. 2003. *National Review of Successful and Innovative Restoration Projects.* Prepared for NOAA Coastal Services Center, by Battelle Marine Sciences Laboratory, Sequim, Washington.